Summit erosion rates deduced from ^{10}Be: Implications for relief production in the central Appalachians

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ABSTRACT

We have measured erosion rates using ^{10}Be from bare-bedrock surfaces exposed at high elevations at Dolly Sods, West Virginia, a classic Appalachian paleoperiglacial plateau. The mean erosion rate from nine samples is 5.7 m/m.y., significantly lower than previously estimated periglacial erosion rates in this region. Measured bare-bedrock erosion rates likely represent the rate at which the highest portions of this broad upland are being lowered. Fluvial incision rates measured in the region over similar time scales are ≥2 times faster, suggesting relief is increasing in this portion of the Appalachians. This observation of increasing relief is inconsistent with prior work suggesting that the central Appalachian landscape is in dynamic equilibrium or currently decreasing in relief. We hypothesize that late Cenozoic climate change has accelerated fluvial incision rates, creating a disequilibrium landscape with growing relief with hillslopes undergoing adjustment to increased fluvial incision rates.

Keywords: erosion, relief, cosmogenic nuclides, landscape evolution, Appalachians.

INTRODUCTION

Hack (1960) proposed the concept of dynamic equilibrium, wherein "all elements of the topography are mutually adjusted so that they are downwasting at the same rate" (p. 85), from observations in the central and southern Appalachian landscape. Recent work in the Great Smoky Mountains using cosmogenic radionuclides to determine basin-averaged erosion rates suggests that basins of differing size and underlying geology erode at similar rates of ~25–30 m/m.y. (Matmon et al., 2003a, 2003b). Ridge crest erosion rates, bare-bedrock erosion rates, and longer-term exhumation rates determined from thermochronology are similar to the basin-averaged rates, supporting a state of dynamic equilibrium in the Smokies (Matmon et al., 2003a).

This proposition of late Cenozoic dynamic equilibrium in the Appalachians contrasts with increases in relief documented in other mountain ranges over the same period (e.g., Gilchrist et al., 1994; Montgomery, 1994; Small and Anderson, 1995, 1998; Montgomery and Greenberg, 2000). The late Cenozoic transition to rapidly changing climate conditions 3–4 m.y. ago may have led to a widespread acceleration of fluvial and glacial erosion rates (Peizhen et al., 2001; Molnar, 2004), leading to relief production as valley erosion rates increased relative to summit-lowering rates (e.g., Molnar and England, 1990; Small and Anderson, 1995, 1998). Along the eastern North American margin, sedimentation rates doubled between the late Miocene and the Quaternary in offshore basins receiving sediment from the central Appalachians (Poag and Sevon, 1989). In eastern North America, fluvial incision rates deduced from terrace sequences appear to have increased since the late Miocene, perhaps in response to long-term cooling and base-level lowering (Mills, 2000). If offshore sedimentation rate increases are the result of accelerated river incision, and if upland erosion rates are not as rapid as fluvial incision, then topographic relief may actually be increasing in the central Appalachians during the late Cenozoic.

Previous work on central Appalachian summits, however, suggests that rapid erosion under periglacial climates has led to a decrease in relief. Braun (1989) obtained upland erosion rates of ~75–300 m/m.y. by estimating the volume of colluvium from three locations in the central Appalachians and dividing by an assumed duration of periglaciation. As modern basin-averaged erosion rates estimated from sediment fluxes are significantly lower, Braun (1989) hypothesizes that periglaciation is the dominant erosional process in the central Appalachian uplands and is most efficient during glacial periods. Assuming that periglaciation is the dominant upland erosional process (e.g., Clark and Hedges, 1992), the rate of relief change in the central Appalachians is therefore determined by the difference between upland-lowering periglacial erosion and valley-deepening fluvial erosion over glacial/interglacial time scales. If periglacial erosion rates are indeed more rapid than fluvial incision as suggested by Braun (1989), the result of climate cooling in the central Appalachians has been the acceleration of upland erosion rates and a decrease in relief during the late Cenozoic.

These three contrasting hypotheses pose the question as to the direction of relief change and the existence of dynamic equilibrium in the central Appalachians. To address the direction of relief change, quantifying the rate of elevation change of the lowest and the highest points in the topography is necessary. In this paper, we use bare-bedrock erosion rates obtained using ^{10}Be on the Dolly Sods Plateau, West Virginia, a classic Appalachian paleoperiglacial landscape (Clark and Hedges, 1992). We have specifically chosen a paleoperiglacial summit to allow us to assess relief change in a location where summit erosion rates have been hypothesized to be particularly rapid, allowing us to simultaneously address the following questions: (1) Is relief changing in the central Appalachians? (2) Are bare-bedrock erosion rates comparable to the rapid erosion rates proposed earlier (e.g., Braun, 1989)? (3) How do bare-bedrock erosion rates here compare to modern periglacial and other environments?

STUDY AREA AND SAMPLING SITES

Dolly Sods, West Virginia, is a broad, gently rolling upland above ~1200 m along the Allegheny Front and is situated ~300 km southwest of the late Wisconsinan glacial limit (Fig. 1). The upland topography is built largely on the sandstones and quartz conglomerates of the Lower Pennsylvanian Pottsville Group, which are folded into a broad north-northeast–plunging syncline. On this upland are numerous features attrib-

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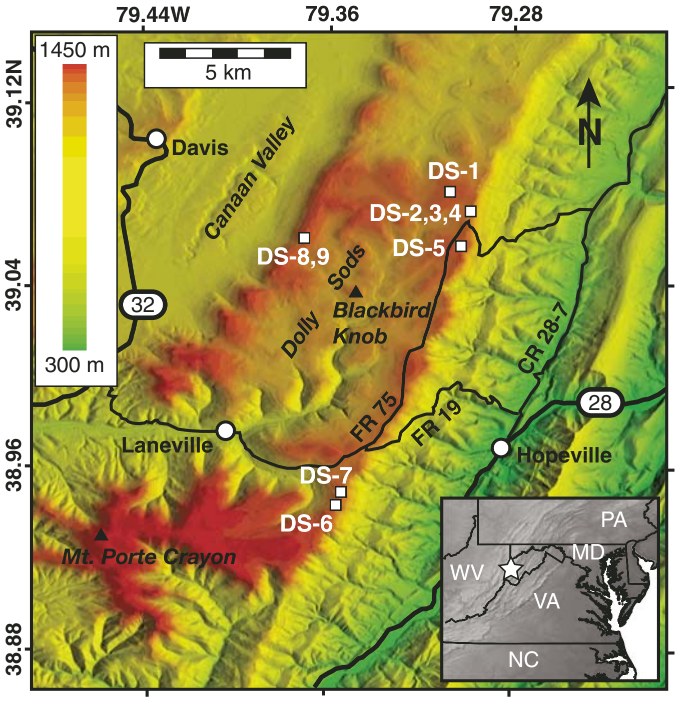

Figure 1. Shaded relief map constructed from 30 m digital elevation model of the Dolly Sods area, West Virginia, showing sampling locations DS-1 to DS-9 and major topographic features. Inset shows general site location. PA—Pennsylvania; MD—Maryland; WV—West Virginia; VA—Virginia; NC—North Carolina.

uted to periglacial activity, including cryoplanation terraces, bedrock tors, patterned ground, block fields, and boulder streams (Clark and Ciolkosz, 1988; Clark and Hedges, 1992).

We collected rock samples from bedrock tors, outcrops, and large detached bedrock blocks in their original location and orientation (Fig. 2), and measured the abundance of the cosmogenic radionuclide (CRN) ^{10}Be in quartz extracted from the rock (Table 1). The surface areas of the bedrock tors and outcrops range from a few tens to hundreds of square meters and are dictated largely by the spacing of bedding planes and nearly vertical joints. Toppled blocks occasionally litter the area at the base of tors, and weathering pits up to ~0.5 m diameter are found on the top surfaces of the tallest tors. The regolith around the sampled bedrock outcrops contains abundant pebble-sized quartz clasts weathered from the conglomerate. Together, these observations suggest that vertical and horizontal erosion of the bare bedrock is accomplished through a combination of joint block

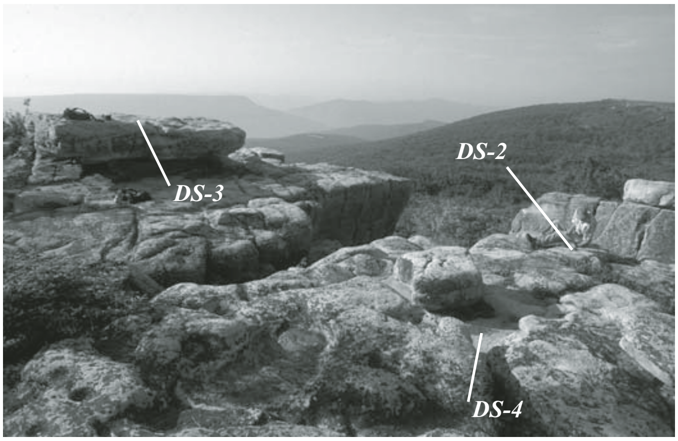

Figure 2. Photograph looking southeast over the edge of the Dolly Sods upland. Shown are sample collection locations for samples DS-2 (lower bedrock surface, note person for scale), DS-3 (upper bedrock surface with well-developed weathering pits), and DS-4 (residual quartz clasts).

removal, dissolution, and granular disintegration. The sampled rock surfaces appear to be eroding by granular disintegration, and we interpret our ^{10}Be concentrations as rock erosion rates.

METHODS

All ^{10}Be samples except one were collected from the tops of tors, bedrock outcrops, and blocks with broad, flat, and nearly horizontal surfaces (Figs. 1 and 2). Samples were collected ≥1.5 m from the edge of the exposures. To determine variations between rates on a tor top and an adjacent bedrock surface exposed at ground level, we sampled from the top of an ~1.5 m tor (DS-3) and the exposed rock adjacent to the tor (DS-2) (Fig. 2). We also collected ~200 quartz clasts weathered from the conglomerate and amalgamated these into one sample (DS-4). As each clast contains a ^{10}Be concentration reflecting the erosion history of the rock from which it was weathered, the rate obtained integrates over many rock erosion histories. The abundance of ^{10}Be in surface samples is interpreted as a steady-state erosion rate (e.g., Bierman, 1994). We do not consider variations in ^{10}Be production rates associated with production-modulating magnetic field strength and orientation variation (e.g., Gosse and Phillips, 2001), as the erosion rate adjustments associated with production rate variations are modest given the goals of this study.

To calculate erosion rates, we use a sea-level, high-latitude spallogenic surface production rate of 5.1 atoms ^{10}Be/g qtz/yr (Stone, 2000). The production rate is scaled to the sample latitude and altitude (Dunai, 2000). The

TABLE 1. EROSION RATES FROM COSMOGENIC RADIONUCLIDE CONCENTRATION

Sample	Sample type*	Elevation (m)	Latitude	Longitude	Production rate correction†	^{10}Be (10^5 atoms/g-qtz)	E (m My^{-1})§	Effective age, T_{eff} (My)§
DS-1	ss outcrop	1250	39.072	79.308	2.49	11.0 ± 0.30	6.3 ± 1.3	90200
DS-2	qc outcrop	1220	39.066	79.309	2.43	12.9 ± 0.47	5.2 ± 1.0	108000
DS-3	qc tor	1220	39.066	79.309	2.43	19.9 ± 0.47	3.3 ± 0.67	167000
DS-4	qtz clasts	1220	39.066	79.309	2.43	11.4 ± 0.27	5.9 ± 1.2	95900
DS-5	qc outcrop	1230	39.052	79.309	2.45	10.2 ± 0.23	6.7 ± 1.3	85000
DS-6	ss tor	1230	38.938	79.362	2.44	7.22 ± 0.18	9.5 ± 1.8	60500
DS-7	ss tor	1230	38.943	79.357	2.45	7.96 ± 0.18	8.7 ± 1.7	66400
DS-8	ss tor	1260	39.053	79.379	2.52	29.9 ± 0.68	2.2 ± 0.47	242000
DS-9	ss tor	1260	39.053	79.379	2.52	21.5 ± 0.49	3.1 ± 0.65	174000

*ss—sandstone, qc—quartz conglomerate, qtz—quartz.
†Calculated using Dunai (2000); correction factors from Lal (1991) produce a ~5% increase in erosion rates.
§Calculated with a sea-level, high-latitude production rate of 5.1 ± 0.3 atoms ^{10}Be g-qtz-yr^{-1} (Stone, 2000) and attenuation length scale of 160 g cm^{-1} (Brown et al., 1992).

mean production rate was determined by integrating over the sample thickness (typically ~5 cm). In all cases, horizon blockage was negligible, and all sampled bedrock surfaces were horizontal (e.g., no self-shielding).

RESULTS AND DISCUSSION

The mean erosion rate from all of the bedrock samples at Dolly Sods is 5.65 ± 2.5 m/m.y. (Table 1). The lowest rates were from the crests of the highest tors with well-developed weathering pits (Table 1), while the most rapid rates were from short tors without weathering pits, and rock outcrops exposed slightly above ground level (Table 1). The residual quartz clast sample (DS-4) yielded a rate of 5.9 ± 1.2 m/m.y., which we interpret as an average erosion rate. As the number of samples is small, we assess the possibility that the rates obtained from our sampled surfaces do not adequately represent erosion rates for the entire population of similar bedrock surfaces on the plateau. To do so, we assume that our sample sites were randomly chosen from this larger population of bedrock surfaces, and that the range of erosion rates across these surfaces is normally distributed. Using a one-tailed t-test, we can reject at a confidence level of 99.9% a null hypothesis that our results could have been obtained from a population of bedrock surfaces whose actual mean erosion rate is even as little as twice that of our sample mean (11.2 versus 5.6 m/m.y.). Hence, it is statistically unlikely that the mean erosion rate is substantially higher on unsampled bedrock surfaces.

The small variation in erosion rates may reflect differences in tor height or episodic erosion of the rock surface. The reduction in erosion rate with increased tor height may result from less effective moisture retention on the surface as the tor crest becomes more exposed (Anderson, 2002; Strudley et al., 2004) or by progressive stripping of soil cover (Bierman and Caffee, 2002). Alternatively, if erosion is episodic, the variation in ^{10}Be rates may reflect varying times since the last erosion event (Lal, 1991; Small et al., 1997). If erosion occurs by grain-by-grain removal and episodic block removal, Lal (1991) suggests that CRN erosion rates will be equal to or greater than the average rate of surface lowering. If erosion occurs only by episodic block removal, deviation of CRN rates from the average depends on how long sampling occurs after the last episodic event (Small et al., 1997). In the Dolly Sods area, toppled slabs at several sites are ~0.2 to ~1 m thick. If erosion occurs by episodic removal of such blocks, individual ^{10}Be erosion rates may deviate from average erosion rates by ±15%–50%; however, sampling numerous outcrops should yield a robust estimate of the average erosion rate (Small et al., 1997).

Our measurements suggest that erosion rates at Dolly Sods are slow and are similar to bedrock erosion rates in other periglacial environments and elsewhere in the Appalachians. The effective ages, T_{eff}, of the samples range from ca. 60 ka to ca. 240 ka (Table 1), and the erosion rates obtained should therefore integrate over, at minimum, one full glacial/periglacial cycle. Small et al. (1997) found an average bare-bedrock erosion rate, corrected for production rate differences, of 7.9 ± 4.1 m/m.y. on summit tors in the central Rocky Mountains and Sierra Nevada, USA. Our upland bare-bedrock rates are similar to nonfluvial erosion rates measured in this region, including on bare granite inselbergs in Georgia (2–10 m/m.y., Bierman et al., 1995), on ridges in Kentucky capped by sandstone and conglomerate (~2 m/m.y., Granger et al., 2001), on soil-mantled hilltops in West Virginia (4–7 m/m.y., Clifton and Granger, 2005), and the bedrock-to-saprolite conversion rate beneath regolith in the Virginia Piedmont (4.5–8 m/m.y., Pavich, 1989). These results are consistent with the conclusion of Small et al. (1997) that alpine bare-bedrock weathering rates are not significantly different from weathering rates obtained from a variety of other settings.

The sampled tors and bedrock outcrops form the highest points on this upland, and bare-bedrock erosion rates on these surfaces should reflect the limiting rate of upland lowering. We consider possible complications with this interpretation here. For tors to grow in height, the surrounding landscape must be eroding at greater rates. Continued growth of tors could lead to their collapse, implying they are ephemeral features whose erosion rate is not representative of overall surface lowering. However, measurements on a tor crest with well-developed weathering pits (DS-3) and bedrock without weathering pits at ground level adjacent to that tor (DS-2) yield rates of 3.3 ± 0.67 and 5.2 ± 1.0 m/m.y., respectively (Fig. 2; Table 1). These results nearly overlap within error, and suggest that bare bedrock adjacent to the tor is eroding only slightly more rapidly than the tor top. We suggest, therefore, that tor erosion rates are a good approximation of the rate at which the maximum elevations on these uplands are being lowered. The rate difference suggests that ~0.7 m.y. are required to develop the ~1.5 m relief between the DS-3 and DS-2 surfaces (Fig. 2). In addition, the rate-averaging sample DS-4 yields 5.9 m/m.y., an average that is not significantly different from the point measurements.

Our measured bare-bedrock rates are much lower than fluvial incision rates averaged over similar time scales in this region. Fluvial incision rates compiled over a broad region of the east-central and southeastern United States average ~30–1000 m/m.y. over ~10^4 to 10^6 yr on Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau rivers (Mills, 2000). A rate of ~60 m/m.y. was obtained by Springer et al. (1997) using cave magnetostratigraphy in the Cheat River basin, of which Dolly Sods is part. Incision rates into bedrock obtained from adjacent basins include ~50–160 m/m.y. obtained from cave magnetostratigraphy and ^{10}Be dating of terraces on the James River, Virginia (Erickson and Harbor, 1998; Hancock and Harbor, 2003), ~20 m/m.y. from CRN dating of fluvial terraces on the New River (Ward et al., 2005), and ~600–800 m/m.y. during the late Pleistocene from CRN dating of strath surfaces on the Potomac and Susquehanna Rivers (Reusser et al., 2004). If these rates are indicative of incision rates in this region, the difference between our bare-bedrock, summit-lowering rates and the fluvial incision rates suggests a disequilibrium Appalachian landscape with topographic relief increasing by ~10–790 m/m.y.

Our proposal for increasing relief is consistent with observations made in adjacent physiographic provinces. On the Appalachian Plateau, Granger et al. (2001) document incision rates on the Green River, Kentucky, of ~30 m/m.y., with adjacent ridgetop erosion rates of only ~2 m/m.y. Similarly, the New River Gorge is currently increasing in relief through differential erosion (Clifton and Granger, 2005). Flexural modeling of the middle Atlantic passive margin suggests average Piedmont denudation rates of ~10 m/m.y., while incision rates calculated from Susquehanna River terraces have increased from ~10 m/m.y. to ~750 m/m.y. over the last ~10 m.y. (Pazzaglia et al., 1998; Mills, 2000). Similarly, Hancock and Harbor (2003) propose increasing relief in the central Virginia Piedmont over at least the last 1 m.y., as James River incision rates are significantly more rapid than the Piedmont interfluve-lowering rates measured by Pavich et al. (1985).

Our observation of increasing relief is inconsistent with an Appalachian landscape that is currently in dynamic equilibrium as posed by Hack (1960). It is possible that we have captured a landscape at Dolly Sods that is currently undergoing a transition toward dynamic equilibrium, with only localized disequilibrium and relief growth produced by a resistant caprock on which erosional processes are slow. Given observations of disequilibrium elsewhere in this region, however, we suggest that the growth of local relief in this portion of the Appalachians could reflect ongoing landscape disequilibrium induced by the onset of rapid climate fluctuation during the late Cenozoic. Climate change has resulted in the acceleration of fluvial incision rates (e.g., Mills, 2000), and hillslope erosion rates may not have had time to adjust fully to this accelerated incision. Theoretical treatments suggest that landscape disequilibrium is to be expected in the Quaternary, as response times in landscapes dominated by fluvial incision are longer than time scales associated with major climatic fluctuations (e.g., Whipple, 2001). The apparent late Cenozoic acceleration of fluvial incision rates in east-central North America may therefore be a local response to late Cenozoic climate and/or base-level changes (Mills, 2000; Peizhen et al., 2001;

Molnar, 2004). Rather than an Appalachian landscape locked in dynamic equilibrium (Hack, 1960) or evolving to transport material generated by rapid periglacial weathering (Braun, 1989), the landscape may be undergoing adjustment to climatically driven increases in the rate of fluvial incision, resulting in landscape disequilibrium and relief generation.

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